Report for 2001GA4701B: Agricultural Drought Assessment and Forecasting for the Southeastern United States

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Report Follows:

Agricultural Drought Assessment for the Southeastern United States

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Abstract

The water resources systems of the Southeastern U.S. are increasingly stressed by various demands. This stress is magnified during the periodic periods of drought that occur in the region, and agriculture is particularly affected by these droughts. Recent public policy has attempted to mitigate the impacts on farmers, but reliable methods of drought assessment and forecasting are needed to allow efficient policy implementation. A methodology is presented to assess the effects of droughts on crop yields, irrigation demands, and the full yield-irrigation relationship. The technique utilizes irrigation optimization algorithms coupled with physiologically based crop models. Ensembles of climatic forcing allow for quantification of the stochastic crop-water production function at specific sites and quantification of the changes in this function in drought periods. Data needs for assessment are discussed as well as sensitivity of the methodology to some input parameters. The technique is applied to four case study sites in southwestern Georgia, and potentially useful information is derived. Options for drought forecasting are briefly discussed.

1. Introduction

As population growth and economic development continue in the southeastern United States, water resources once thought inexhaustible are increasingly stressed. This fact has become profoundly evident during the region's drought of the past several years. Competing demands for water resources have led to inter-state as well as intra-state conflicts in the political and legal realms. Agriculture in the region is a consumer of surface water and groundwater, a party to the ongoing conflicts, and particularly vulnerable to climatic variation. While rainfall is adequate in wet and average years for farms to thrive with minimal water consumption, irrigation is required in drought years if farms are to simply survive.

Previous research has addressed some characteristics of drought effects on agriculture in the region. Hook (1994) used crop models to estimate irrigation needs and crop yields for corn, soybeans, and peanuts for the 15 driest years of a 53 year record. His results showed average yield losses of between 64% and 75% in the identified drought years. Irrigation requirements were computed using a soil moisture triggering threshold calibrated to produce 90% of fully irrigated yield. Irrigation requirements were found to vary with soil type. Meteorological variation in the spatial domain was not considered. Hook and Thomas (1995) conducted a similar study whereby the effects of "emergency" curtailments of irrigation were assessed for three policies: 30-day restrictions, 60-day restrictions, and complete restrictions. Economic losses were estimated for several dates of policy implementation within the growing season. Costs were found to vary by length of restriction, date of restriction period, crop, and soil type. For the Flint River Basin of southwest Georgia, costs of water conservation ranged from $531 per million gallons for corn under a 30-day restriction imposed in July to $2,388 per million gallons for peanuts under a 30-day restriction imposed in August.

The State of Georgia currently operates a program of compensation to farmers for not irrigating in years declared as probable drought years by the state on March 1. The current state of climate prediction capability for the region is limited, however. Moreover, current policy as legislated by the "Flint River Drought Protection Act" (OCGA 12-5-540) is an "all-or-nothing" proposition for farmers. The possibility of irrigation quantity limits is not part of the present system, although such limits might be preferable for some or all concerned parties.

Compounding the difficulties of policy implementation is the lack of documented knowledge on irrigation use in the region. Georgia has not maintained measured records of irrigation applications by production farms prior to 1998 when the “Ag WATER PUMPING” project commenced to monitor irrigation application at about 2% of permitted wells in the state (Thomas et al. 2001). Prior to this program perhaps the best information available was estimates made by extension agents published every five years in the USDA Farm and Ranch Irrigation Survey (e.g., NASS 1998). However, the figures included in that publication are statewide averages and are described therein as “rough estimates” (pp. XVII-XVIII). The infrequent and spatially aggregated nature of these estimates make them unsuitable for use in determining drought effects or policy needs. Data from the Ag WATER PUMPING project will be valuable, although it is not scheduled for public release at this time, and its limited temporal extent will be a shortcoming until long-term monitoring has been achieved. Investigation of historical records of crop production is also inadequate for the purposes of discerning drought effects on agriculture. As an example, Figure 1 shows historical values of peanut yield for Tift County, Georgia (NASS 2002). The dominant mode of variation in the time-series is a large, long-term increase in crop yields from the beginning of the data in the 1930’s until the late 1970’s. This increase in magnitude is due to a “technology effect” of improved crop varieties, management practices, mechanization, etc. Moreover, measured field yield at the county scale is an undetermined mixture of irrigated and non-irrigated production, which makes identification of drought signals very difficult.

This report presents findings of a preliminary investigation into new technologies relevant to the problem of assessing, forecasting, and managing for agricultural droughts in the Southeastern U.S. Specifically this project has applied recently developed techniques of irrigation planning and determination of crop yield-irrigation relationships to the case of crops grown in southwest Georgia. Information on the variability of yield-irrigation response with climatic variability is determined. The possibility of using climatic teleconnections to forecast agricultural trends is discussed. Current deficiencies in data for application of these techniques are determined. Finally, future research efforts applicable to this issue are identified.

2. Methodology

The methodology for this study includes the following items: physiologically based crop modeling, optimization of irrigation schedules and yield-irrigation relationships, input data determination, study site specification, and drought period identification. These items are described in the following sections. The assessment process follows.

2.1. Physiologically Based Crop Modeling

Simulations of crop growth were conducted using the Decision Support System for Agrotechnology Transfer (DSSAT) suite of crop models. (Tsuji et al. 1994). These models are first-principles, physiologically based models of crop growth and development processes, which include daily meteorology, soil/plant water balance, phonological development, photosynthesis, carbohydrate partitioning, and management inputs among other items. The models have been developed and refined by a global cadre of scientists over the past two decades. Verification studies are abundant and show the models to be reliable.

Of particular interest to this study is the water balance component of the models. The water balance sub-model is described in detail by Jones and Kiniry (1986) and Ritchie (1998). Verification of the water balance routines has been presented by Ritchie (1972), Gabrielle et al. (1995), and Brumbelow and Georgakakos (2001) among others. The sub-model includes routines for calculation of runoff, downward soil moisture transport, evaporation from soil, transpiration from plants, root water uptake, capillary rise, and soil moisture content updating. Periods of drought stress are identified by deficiencies in plant water balance, namely when the ratio of root water uptake (inflow of water to plant) to transpiration (outflow of water from plant) falls below unity. A "soil water deficit factor" calculated as this ratio is then factored into numerous process equations.

The crop models include some routines that were not utilized in this study. Nutrient processes and damages due to pests and disease were omitted as the focus of the study was on drought stresses and irrigation. As agriculture in the region consistently uses effective programs of fertilization and pest control, this assumption is not significant.

2.2. Optimization of Irrigation Schedules and Yield-Irrigation Relationships

In contrast with previous studies, this research included determination of the entirety of the yield-irrigation relationship. That is, the full crop water production function (CWPF) was derived for each growing season in the study period rather than a single irrigation value. The method for determining CWPF's was the "Simple Yield-Irrigation Gradient" (SYIG) algorithm (Brumbelow 2001, Brumbelow and Georgakakos 2002b). This algorithm uses determination of marginal values of differential irrigation allocations to schedule additions to existing irrigation schedules in a repetitive manner. By starting at the zero-irrigation point and iterating until the full irrigation plateau is reached, a full CWPF is obtained. Since the algorithm is coupled with the capabilities of physiologically based crop models, irrigation scheduling is accomplished accounting for soil moisture conditions, solar radiation, dynamic rates of phenological development, and other physiological circumstances not accounted for by traditional irrigation scheduling methodologies (e.g., reference evapotranspiration-crop coefficients, Doorenbos and Pruitt 1977, etc.). More advanced algorithms in the YIG family have been developed, and these techniques provide optimized results. However, their computational requirements are greater, and they were not used in the interest of time of execution.

2.3. Input Data Determination

A variety of input data were needed for the study. Soils data were obtained from the USDA Natural Resources Conservation Service (NRCS) State Soil Geographic Database (STATSGO, NRCS 1994). The soil maps of this database were reviewed in a geographic information system to determine relevant variation of soils in the locales under investigation. Where soil types differed significantly in the vicinity of a study site, multiple soil types were included in the study.

Daily meteorological data were needed for six parameters as input to the crop simulations: precipitation, maximum temperature, minimum temperature, hours of bright sunshine, relative humidity, and wind run. Data for the first three parameters were easily obtainable for many stations from the National Climatic Data Center's online archives (NCDC 2002). The last three parameters posed some difficulties, as they were not commonly available for many stations.

Sunshine hours were available for the period January 1965 to May 1996 only at Macon, Georgia, and Montgomery, Alabama, in the region. Since incoming solar radiation drives photosynthetic production, knowledge of sunshine hours is very important for crop simulations, and final yield estimates can be quite sensitive to this parameter. For this reason it was decided to limit the scope of the study to the period for which measured sunshine hours were available and to use the Macon data for all sites since it was representative of the values for the region.

Relative humidity and wind run were also not commonly available in the region. As the sensitivity of crop yields to these parameters is not as great as other variables, simple estimation formulae were used to approximate values for these parameters. Relative humidity has been observed to follow a roughly sinusoidal trend in the region with some noise and elevated values during periods of precipitation (see Figure 2). Therefore, an estimation equation based upon this pattern was used for each station in the study:

$$RH = \min\left[1.00,\ \ 0.60 + \cos\left(2p \cdot \frac{(DOY - 80)}{365}\right) \cdot 0.20 + P \cdot 0.35\right] \qquad \textbf{(1)}$$

where RH is daily relative humidity (0.00 – 1.00), DOY is the Julian day of the year (1 – 365), and P is daily precipitation in inches. Wind run was estimated by a simple random number generator with lower and upper bounds of 0 and 20 miles per hour, respectively. Figure 3 shows typical measured values from the region, and it is seen that this approximation is adequate.

2.4. Study Site Specification

Four sites in southwestern Georgia were chosen for the study: Tifton, Colquitt, eastern Mitchell County, and southwestern Mitchell County. Both Mitchell County sites utilized meteorology from the Camilla station. Selection of the sites encompassed a variety of soil types and locales in the region, yet allowed for comparative analysis of sensitivity of results to meteorology under common soil and sensitivity to soil under common meteorology. Three of the sites (Colquitt and the two Mitchell County sites) are located in the hydrologically sensitive lower Flint River Basin and should serve as suitable benchmarks for further studies in that watershed. The Tifton site is collocated with an extensive agricultural experiment station and is thus well suited for calibration and verification against previously collected data at that site. Table 1 below relates basic information about the study sites, and Figure 4 shows the location of the sites as well as the extent of the soil types included in the assessment.

As is seen in Table 1, the Colquitt and E Mitchell County sites are both underlain by the soil noted as MUID GA050. The distance between the two sites is about 40 miles (64.5 kilometers), and separate records of precipitation and daily temperatures were used for the two sites. These circumstances allow for a preliminary test of the assessment technique for its sensitivity to site-specific meteorology with other factors held constant. In a similar fashion, the two Mitchell County sites share common meteorology from the Camilla station, but occur on two different soil types, GA050 and GA 060.

Table 1. Study sites included in the assessment case study

Name	Approximate Position	Soil Type (STATSGO MUID)	Meteorological Station
Tifton	31.45º N, 83.48º W	GA057	Tifton Exp Sta
Colquitt	31.17º N, 84.77º W	GA050	Colquitt 2 W
E Mitchell Co.	31.27º N , 84.08º W	GA050	Camilla 3 SE
SW Mitchell Co.	31.16º N , 84.35º W	GA060	Camilla 3 SE

2.5. Drought Period Identification

Within the 31 year period of recorded meteorology available for the study, it was necessary to determine when droughts occurred. Two non-independent criteria were used for this purpose. First, calculations of the Palmer Drought Severity Index (PDSI) were obtained from the National Climatic Data Center for climate division GA-7 (NCDC 2002), which includes the southwestern corner of Georgia (see Figure 5). A low-pass filter (4-year moving average) was applied to the index values. These filtered PDSI values are graphed in Figure 6a.

Additionally, the aggregate monthly precipitation values for GA-7 were also obtained from NCDC (2002). The long-term average precipitation was computed for each of the 12 months of the year using all data from 1895 to 2002. Then, the historical values of measured precipitation were compared to the long-term averages to find a time-series of monthly deviations from average. Again, a low-pass filter (4-year moving average) was applied to the time-series of deviations. The final product is shown in Figure 6b.

The two criteria are very similar upon comparison. The precipitation deviations tend to be a bit noisier and tend to lead the trends in PDSI by a few months. These observations fall in line with expectation: the PDSI is an attempt to model soil moisture conditions, which lag and dampen precipitation forcing. However, determination of drought periods by either metric yields the same conclusions. Within the study period drought periods occurred in the years: 1968-1970, 1979-1981, and 1986-1990. Because of the lag between precipitation and PDSI, the years 1967 and 1985 should be regarded as “transition” years as they experienced reduced rainfall but not the reduced soil moisture values represented by the PDSI.

2.6. Assessment Process

For each of the four sites, crop growth simulations were conducted for two crops, maize and peanuts, both economically important and commonly grown in the region. For maize simulations, planting date was set at April 15, for all sites and all meteorological years. The maize cultivar used was Pioneer 3147. Planting date for peanut simulations was set at May 15, for all sites and years. The peanut cultivar used was Pronto. The

Simple YIG algorithm was used in conjunction with the appropriate DSSAT model to determine the crop-water production function for each crop at each site for all 31 growing seasons (total of 248 functions generated). The 31 functions determined for each crop and site collectively form the crop-water production function probability distribution (CWPF-PD, Brumbelow 2001, Brumbelow and Georgakakos 2002a) for that crop and site. The 8 CWPF-PD's are presented as the "a" part of Figures 7-14. By inspecting the CWPF's of designated drought years, a sub-set of the CWPF-PD is realized, which is ideally indicative of drought effects on crop yield, irrigation needs, and the relationship between the two. The CWPF-PD's of the drought periods are shown with the full CWPF-PD's in the "b" parts of Figures 7-14. This concept and potential forecasting techniques are discussed in the next section.

3. Results and Discussion

Comparison of the two CWPF-PD's in the "b" parts of Figures 6-13 shows a clear distinction between those of the full study period and those of the drought periods. An excellent example of the difference is Figure 8b (maize grown at the Tifton site). For that case the median crop-water production function is almost exactly the same as the 25th percentile function from the full study period for irrigation amounts from 0 to 120 mm. The reduction in rainfed crop yield for the drought median function is 4184 kg/ha from the full period median function, which represents a 49% reduction. For all cases, as the CWPF-PD's reach yield plateaus, they become quite similar (or almost identical in Figure 8a). This phenomenon is expected and has been noted by Brumbelow (2001) and Brumbelow and Georgakakos (2002a): the yield plateau is that region of crop response divorced from moisture stress concerns, and variability in crop yield is determined in that regime by temperature and radiation factors rather than precipitation patterns. Interestingly, the upper quartile of the drought periods' CWPF-PD extends to high yield values for low irrigation amounts, and this occurrence is consistent among the case studies. This skew in the drought period CWPF-PD reflects natural variability in the agricultural system even in periods of pronounced stress and potential uncertainties in the definition of drought. The criteria used to designate the drought periods for this study relied on time-aggregated metrics (4-year moving averages of regional monthly values). In contrast, the crop simulations performed herein assumed spatial points and daily timesteps, and real agricultural systems respond to meteorological events at timescales of minutes. Therefore, the upper quartile spread is perhaps unavoidable and is certainly a consequence of natural variability and differences in system scales.

Sensitivity of the assessment technique to soil type can be understood by comparing the results for the Eastern Mitchell County and Southwestern Mitchell County sites (Figures 11-14). For both peanuts and maize, the two sites have virtually identical sets of CWPF-PD's. This result is not surprising as the two soil types present do not differ greatly in composition as shown in Figure 15a-b or in plant extractable water capacity (Figure 16). The lack of sensitivity observed works to increase confidence in the assessment technique as small changes in soil characteristics are not overly influential. This finding may also justify less intensive modeling efforts on a spatial basis as minor soil differences will not cause different drought responses. However, future investigation must determine the relevant threshold for soil differences to cause changed yield-irrigation response.

Sensitivity of the assessment technique to locality of meteorological observations can be understood by comparing the results for the Colquitt and Eastern Mitchell County sites, which shared the same soil type (Figures 9-12). There are noticeable differences between the CWPF-PD's for both crops at these sites. However, the general character of all distributions of yield-irrigation functions is very similar for the same crop and study period. Again, additional research is merited to determine the limits of geographic commonality, especially in heterogeneous climatic zones. Nevertheless, the present observation affirms that the study methodology is not prone to over-sensitivity to locality of meteorological observations.

The value of CWPF-PD's for drought assessment and management can be realized on multiple fonts. For the individual farmer, the shifted drought distribution provides quantitative information with which to plan field operations. This scenario is especially valid if reliable drought forecasts are available. Using the case of maize grown at Tifton (Figure 8b), management decisions for an anticipated drought season might be as follows. If median rainfed yield granted the farmer an acceptable level of profitability, his target yield would be 8501 kg/ha. Under drought conditions, this target could be produced with 50% reliability with 25 mm irrigation (all irrigation values do not include transmission and application losses). However, net profits would be reduced by irrigation costs, and the farm may not have irrigation capacity for all fields. Thus, a more desirable target might be to achieve 9500 kg/ha with at least 75% reliability. In drought periods this would require 77 mm irrigation. To achieve the same target with 100% reliability would require 172 mm irrigation.

Water resources managers could use the CWPF-PD technique to help shape drought management policy. An example might be to alter the current Flint River Drought Protection Act system of compensating farmers to forego all irrigation on acreage to a system of compensation for reduction in irrigation. A reduction target that might be satisfactory to all parties would be the irrigation level at which drought period CWPF-PD's become sufficiently similar to the distribution of all yield-irrigation functions derived from history. That is, the irrigation target could be set at the point where the inherent variability in the agro-climatic system overwhelms the reduction in function distributions forced by drought conditions. The exact location of this point is likely a subjective determination, but it may be a reasonable policy. In the case of maize grown at Tifton, this target could arguably be set at about 140 mm. This level would be appropriate at the Eastern Mitchell County site, but Colquitt would possibly require a higher target, and Southwestern Mitchell County a lower one. On the whole for the region, a 140 mm target would represent a reduction in irrigation for 14 of the 15 worst drought years identified by Hook (1994). Thus, the policy could have real impact.

The issue of reliable drought forecasts remains a difficult one for the Southeastern U.S. Studies attempting to find links between El Nino-Southern Oscillation (ENSO) phenomena and the region's climate have found weak correlations for winter months (e.g., CPC 2002), but these months are outside the growing season for many important crops. Investigation of the Pacific Decadal Oscillation (PDO, e.g., Mantua et al. 1997). time-series compared to cumulative precipitation anomalies in the region shows that long-term cycles (periods of decades to centuries) may have some correlation. Gulf of Mexico sea surface temperature anomalies also may be correlated in the same cycle as the PDO, which may provide a credible causation for Southeastern U.S. climate. However, significant work remains to be done.

4. Conclusions

This report has presented the preliminary form of a new methodology to assess and aid in decision making for agricultural and water resources systems under droughts. The technique has been applied to maize and peanut cultivation in the hydrologically, economically, and politically sensitive region of southwestern Georgia. It has been demonstrated that the assessment process provides potentially useful information.

Future work is required to refine the presented methodology and expand on its capabilities to provide useful information. The limited meteorological data for the case studies – specifically the limitations in sunshine hours data – hampered the project somewhat. Expansion of the meteorological dataset through statistical techniques of hindcasting, etc., would be valuable and allow for analysis through additional drought periods where precipitation data do exist. As was discussed, the sensitivity tests established that the study techniques are not overly sensitive to geographic heterogeneity, but the thresholds of sensitivity have not been established. Knowledge of these thresholds is needed in order to design appropriate assessment plans. Finally, reliable drought prediction techniques are needed for the Southeastern U.S. The real utility of the study techniques relies on the ability to forecast drought. Without such ability, the methods are limited to ex post analyses. However, it is a hopeful proposition that drought forecasting ability is not far off for the region.

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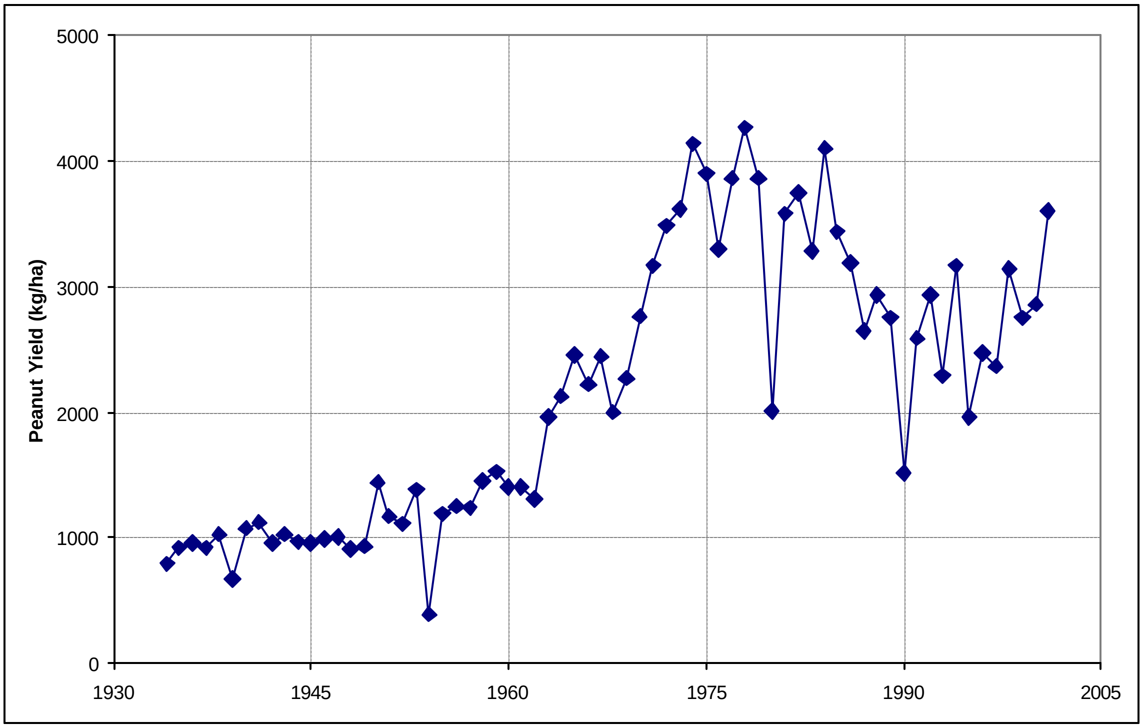

Figure 1. Peanut crop yield observed in Tift County, Georgia, 1934-2001 (NASS 2002).

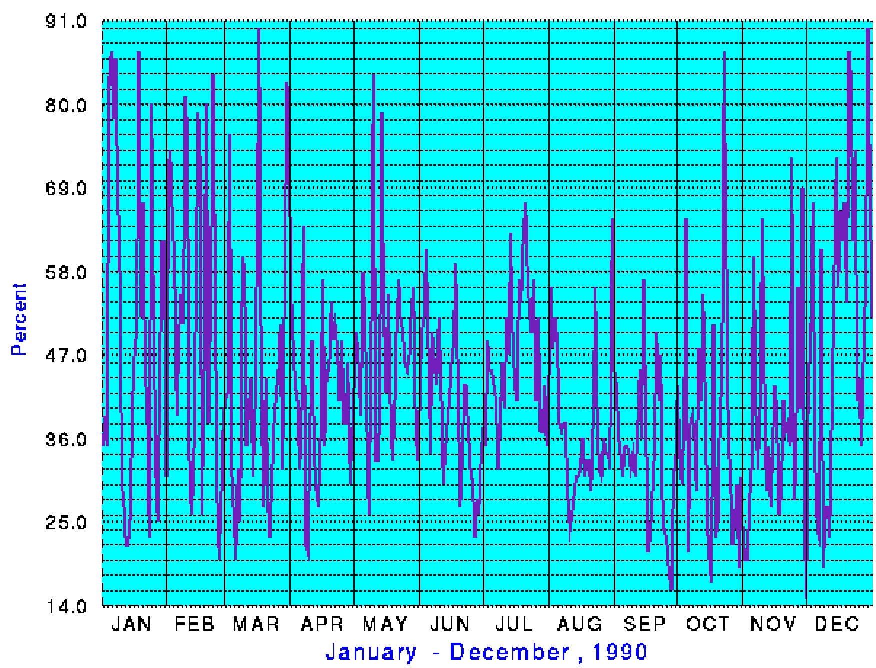

Figure 2. Daily relative humidity observed at Montgomery, Alabama, 1990 (NCDC 2002).

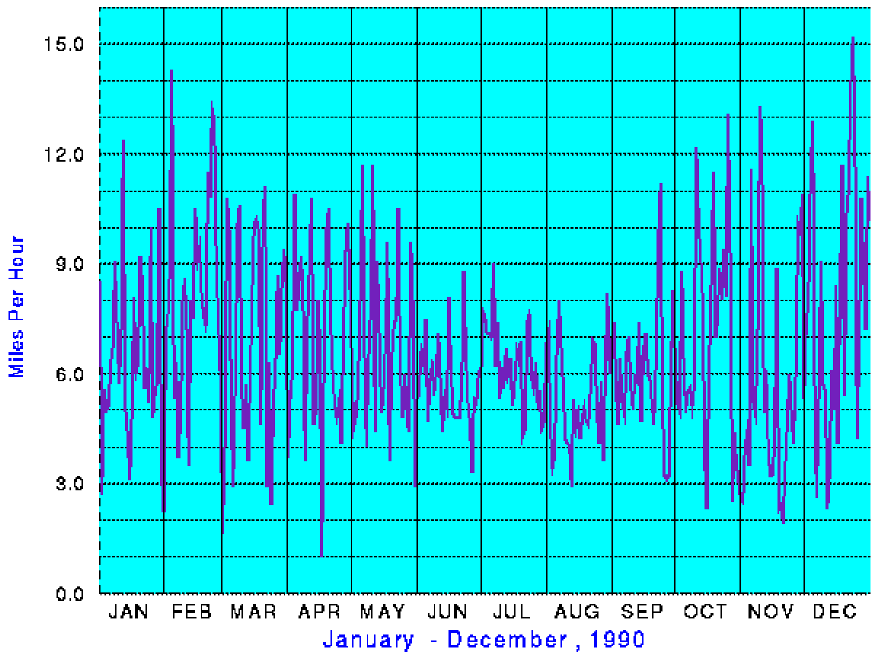

Figure 3. Daily wind speed observed at Montgomery, Alabama, 1990 (NCDC 2002).

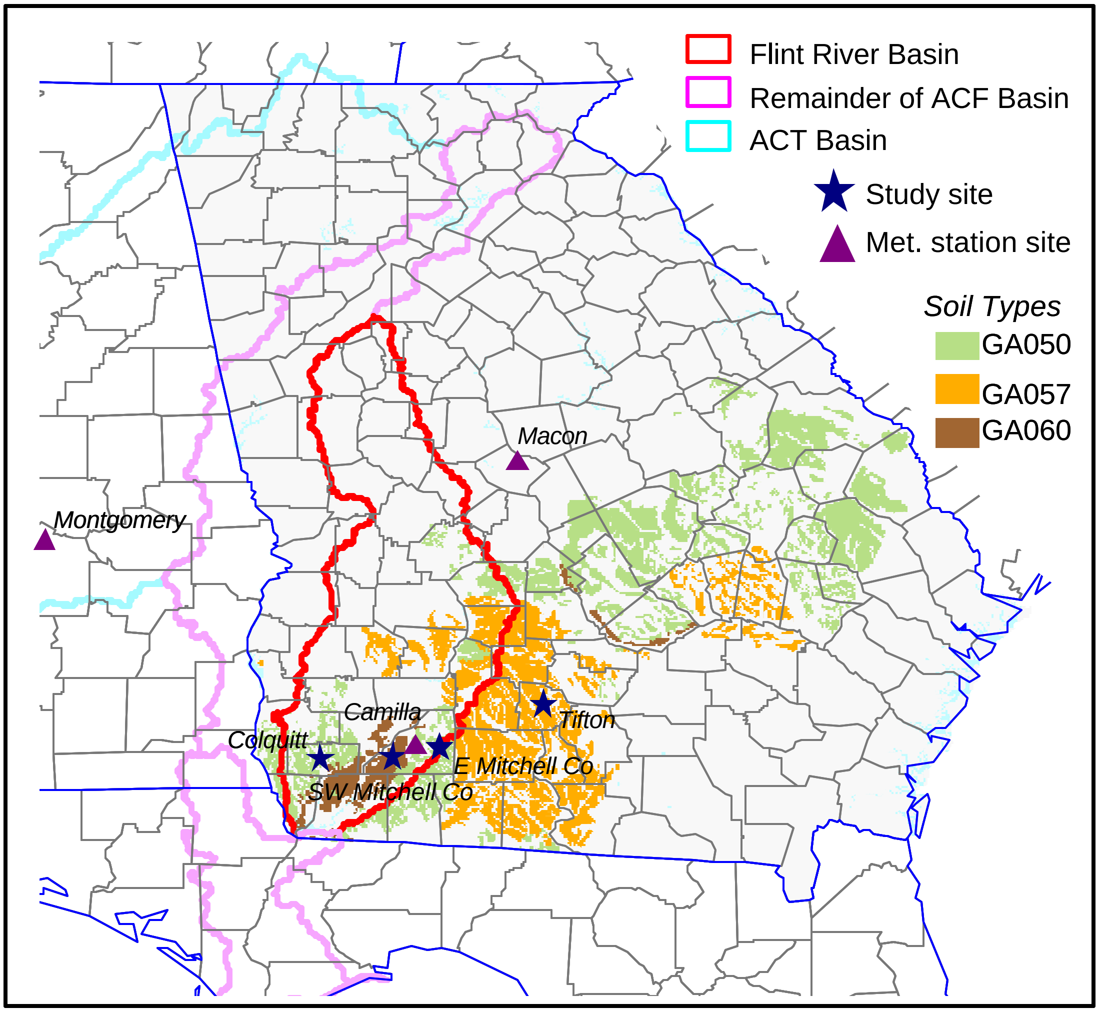

Figure 4. Map of Georgia showing locations of four study sites, other relevant meteorological stations, extent of soil types included in the study, and boundaries of important river basins in the region.

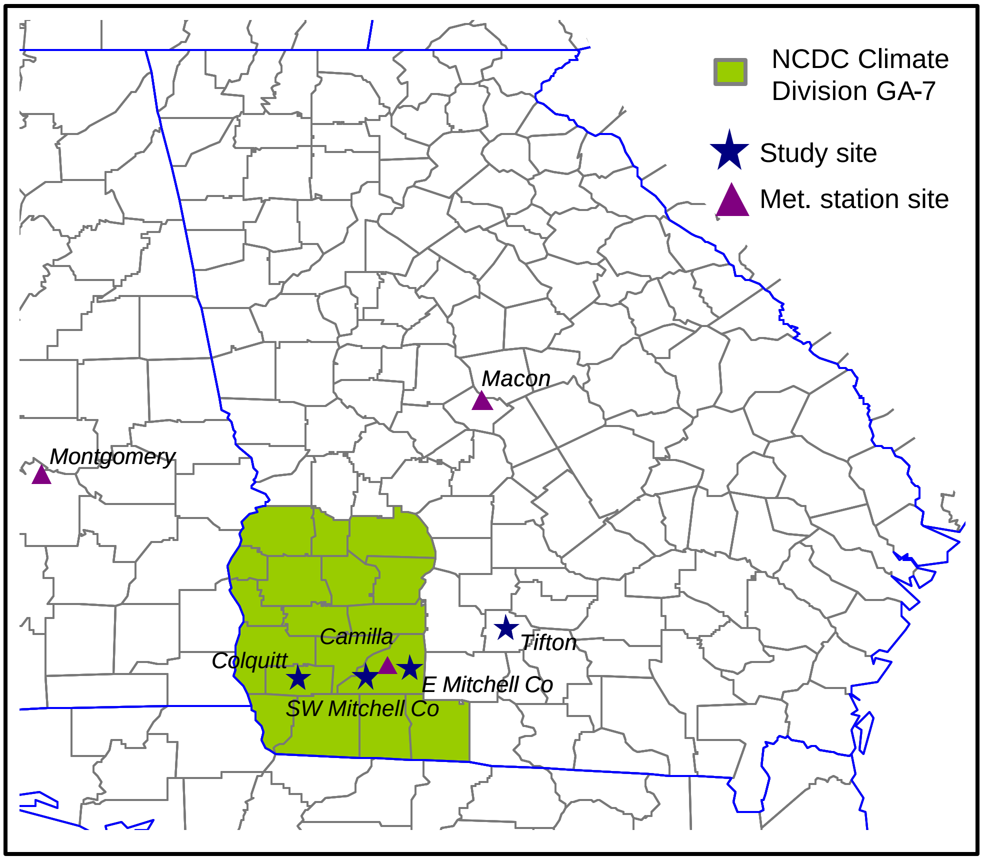

Figure 5. Location of NCDC climate division GA-7.

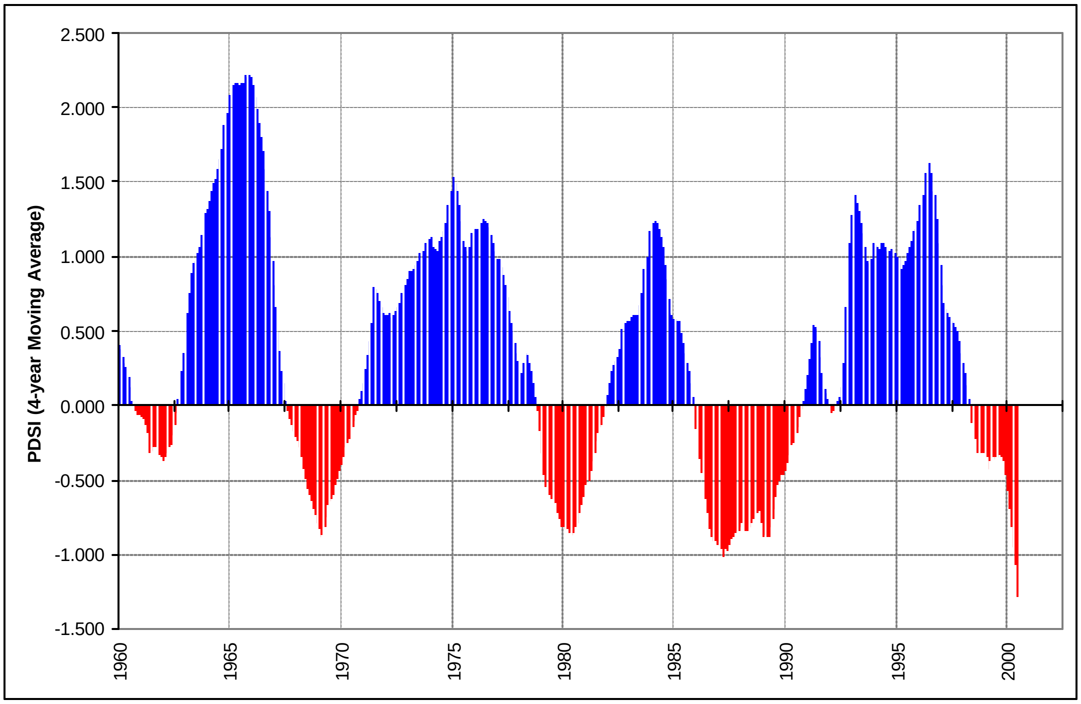

Figure 6a. Palmer drought severity index values for climate division GA-7 (NCDC 2002). The index values have been low-pass filtered to aid in identify inter-annual cycles.

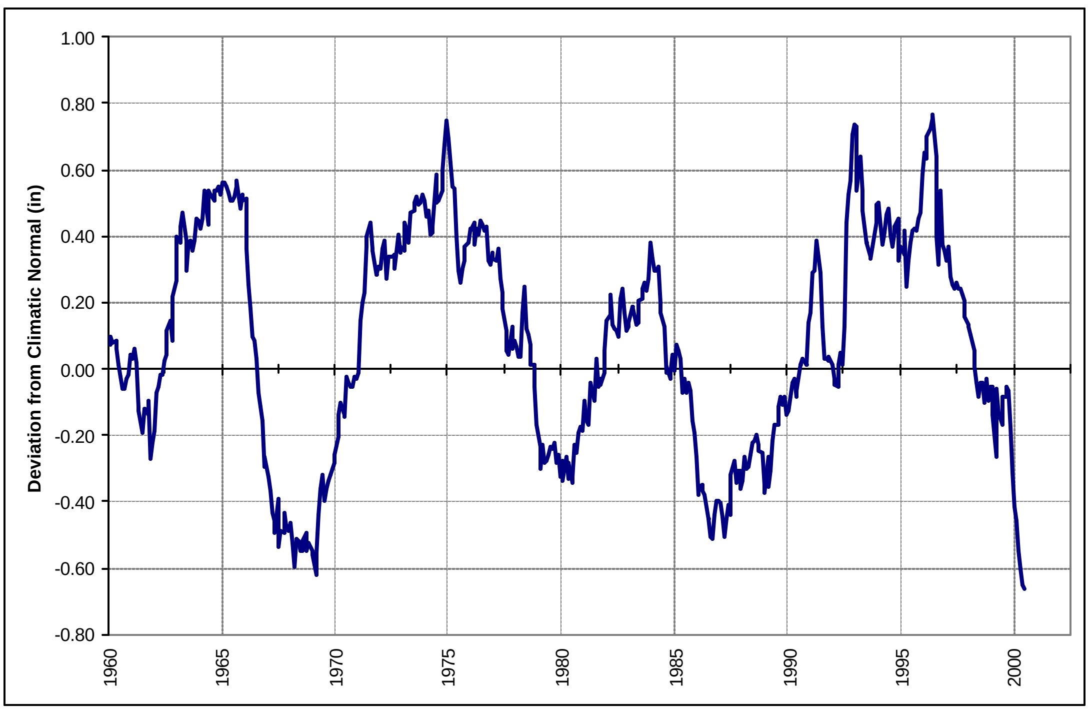

Figure 6b. Deviation of monthly precipitation values from long-term (1895-2002) averages. As above, values have been low-pass filtered.

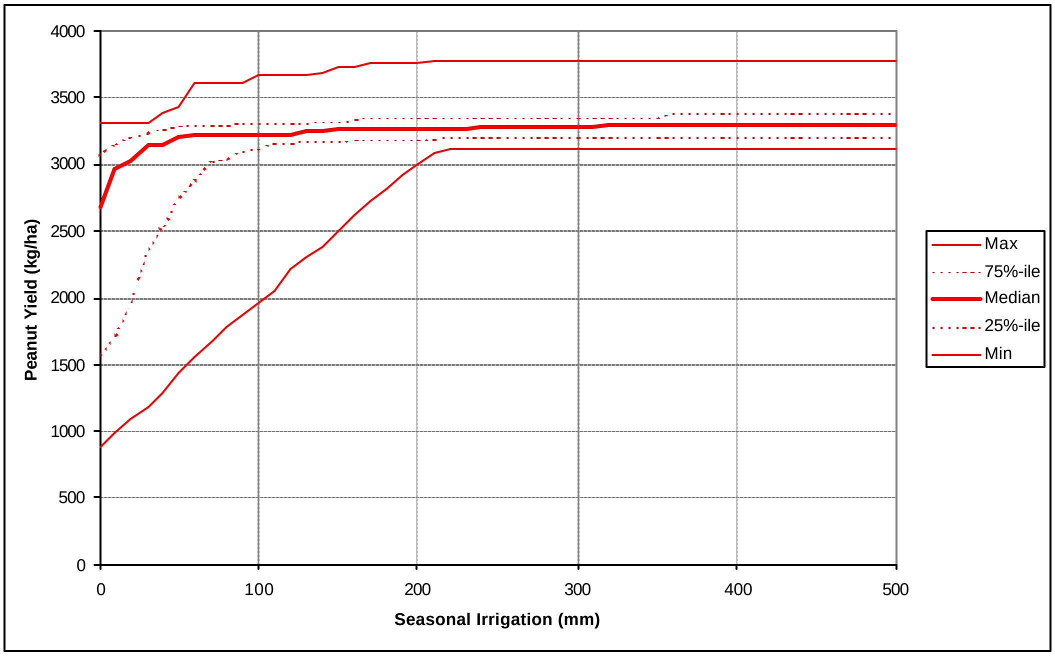

Figure 7a. Crop-water production function probability distribution (CWPF-PD) for peanuts grown at Tifton, full study period of 1965-1995.

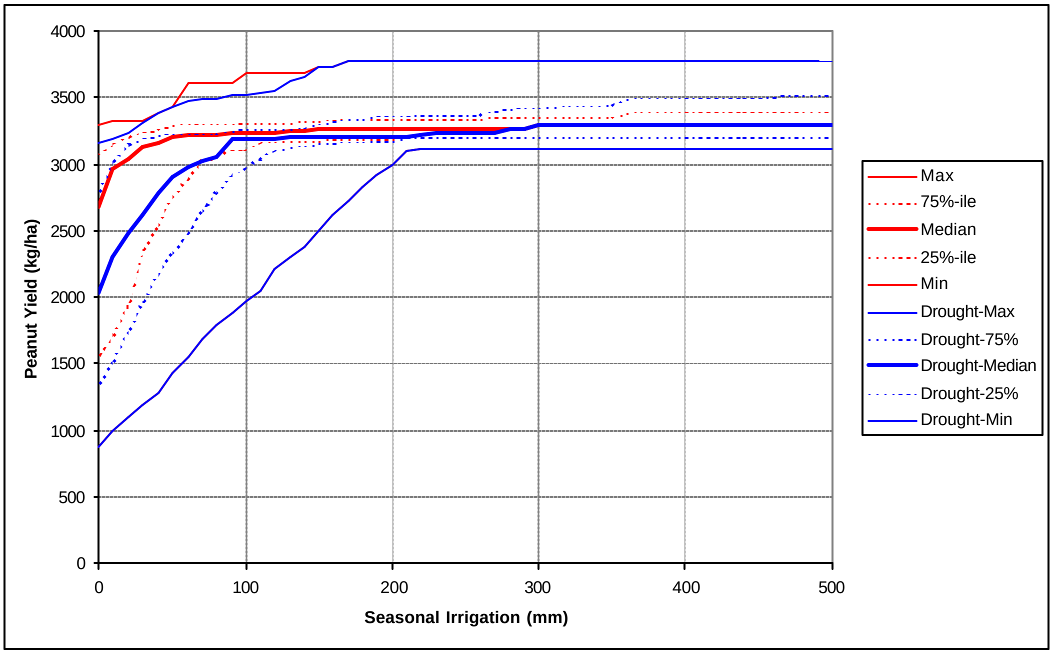

Figure 7b. CWPF-PD for peanuts grown at Tifton for both the full study period (red) and the drought seasons alone (blue).

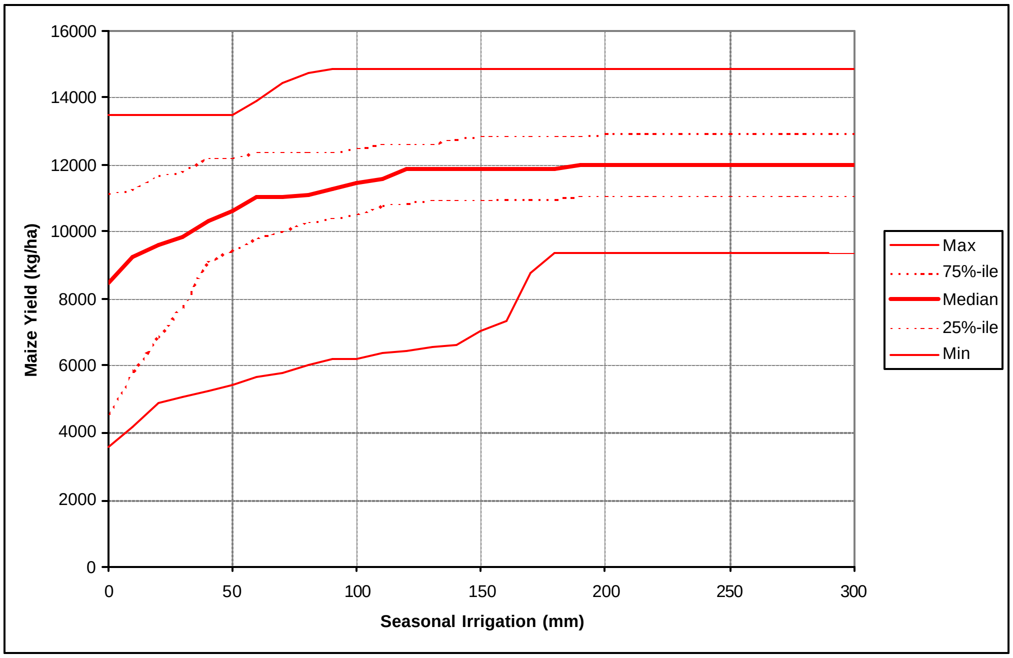

Figure 8a. CWPF-PD for maize grown at Tifton, full study period of 1965-1995.

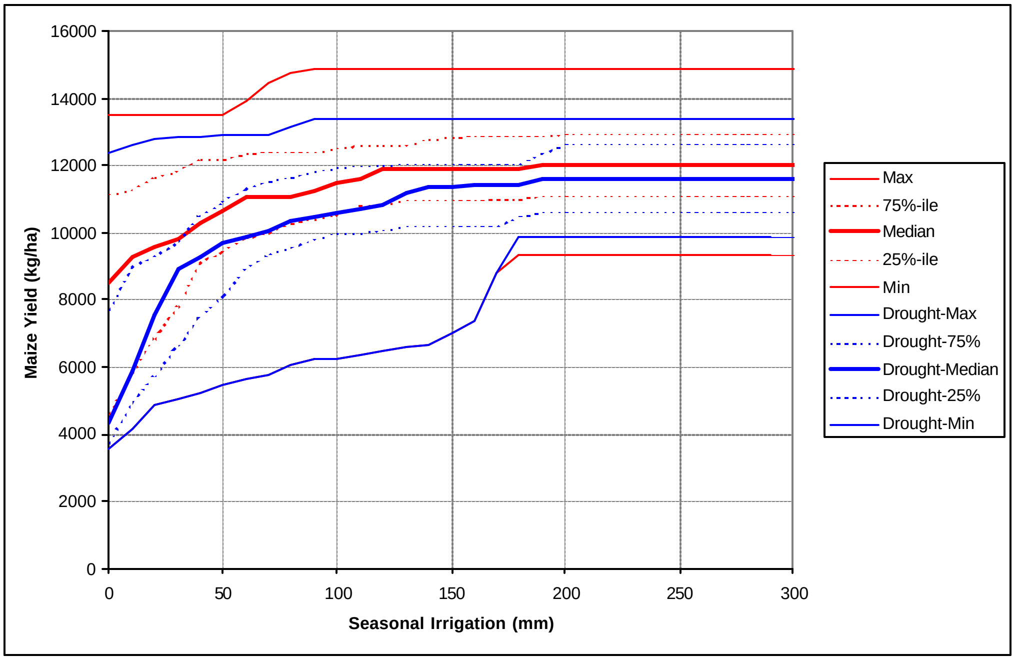

Figure 8b. CWPF-PD's for maize grown at Tifton for full study period (red) and drought seasons alone (blue).

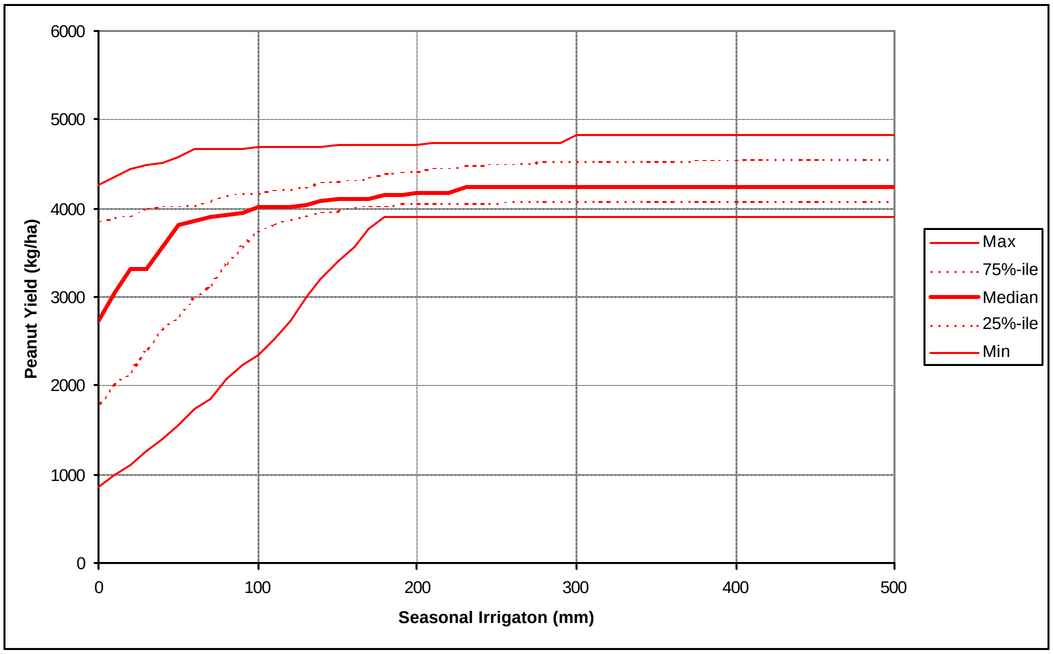

Figure 9a. CWPF-PD for peanuts grown at Colquitt, full study period of 1965-1995.

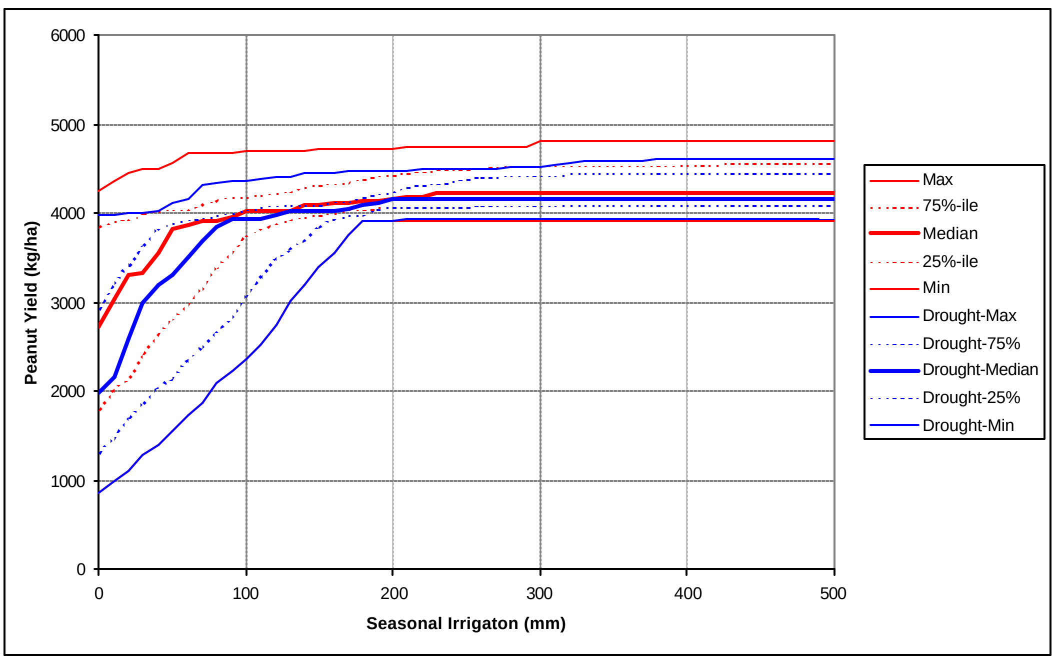

Figure 9b. CWPF-PD's for peanuts grown at Colquitt for full study period (red) and drought seasons alone (blue).

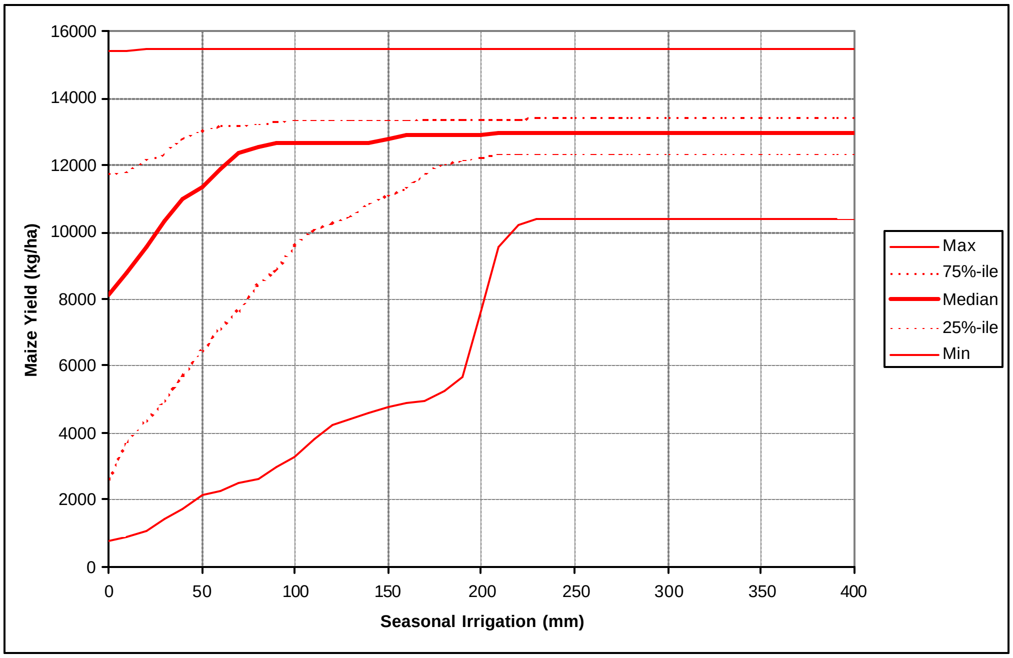

Figure 10a. CWPF-PD for maize grown at Colquitt, full study period of 1965-1995.

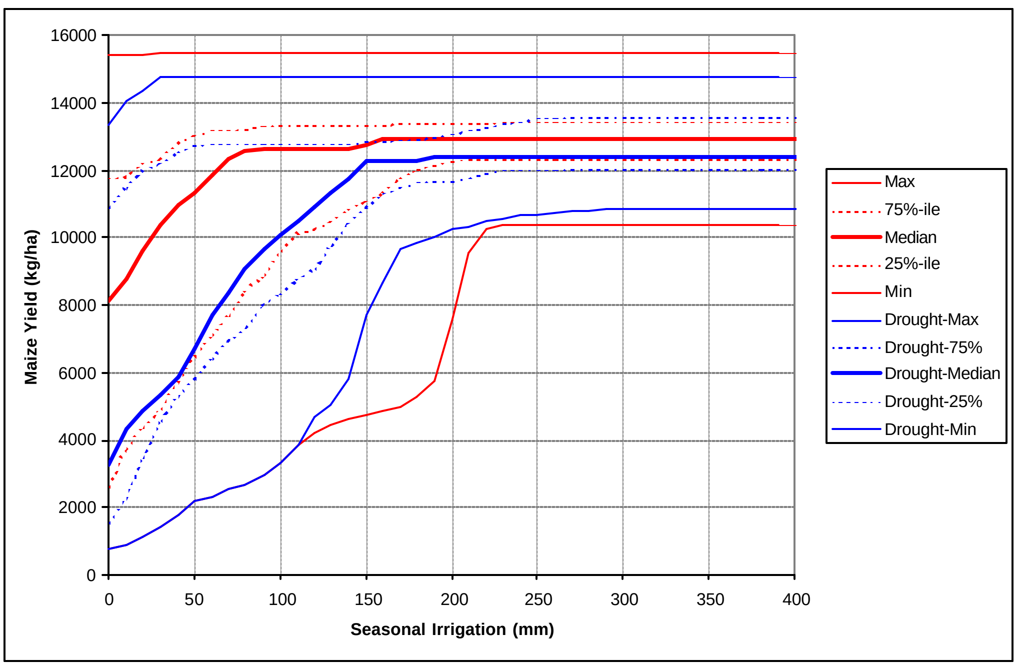

Figure 10b. CWPF-PD's for maize grown at Colquitt for full study period (red) and drought seasons alone (blue).

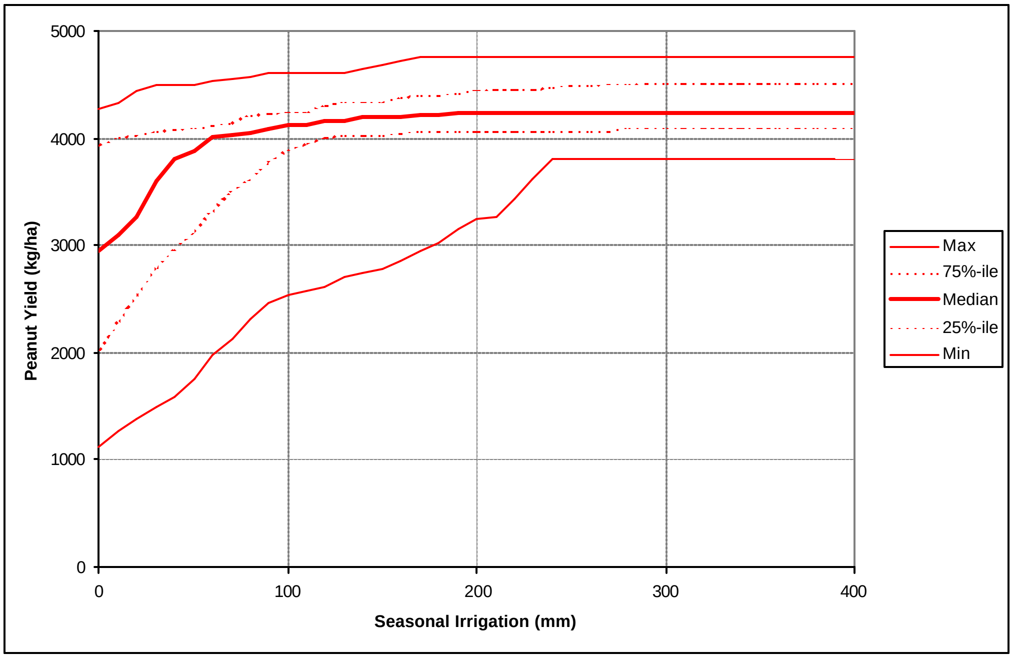

Figure 11a. CWPF-PD for peanuts grown at East Mitchell County, full study period of 1965-1995.

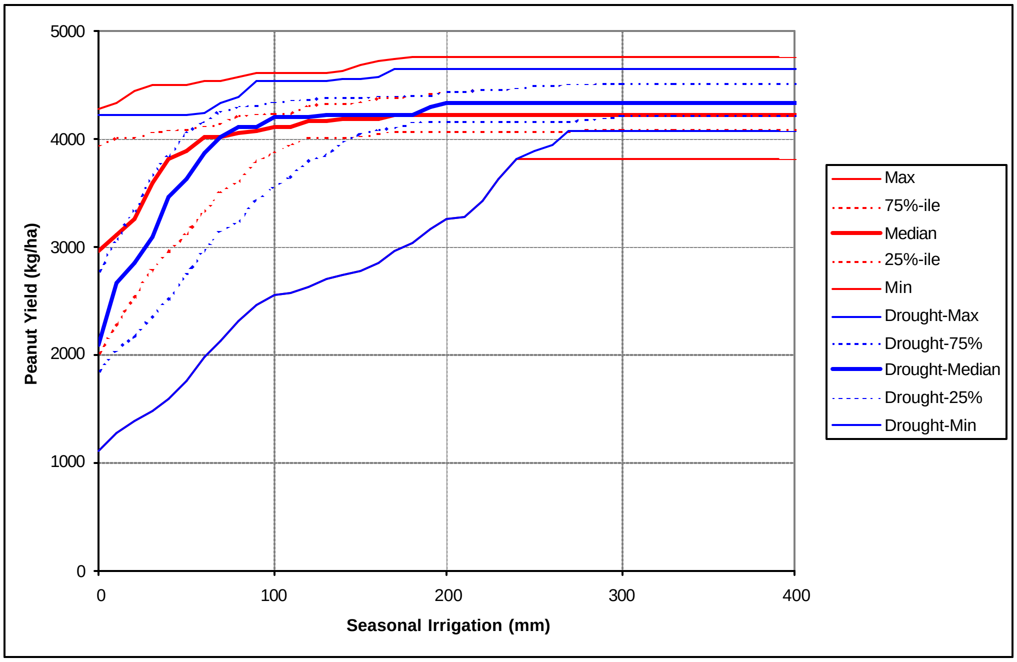

Figure 11b. CWPF-PD's for peanuts grown at East Mitchell County for full study period (red) and drought seasons alone (blue).

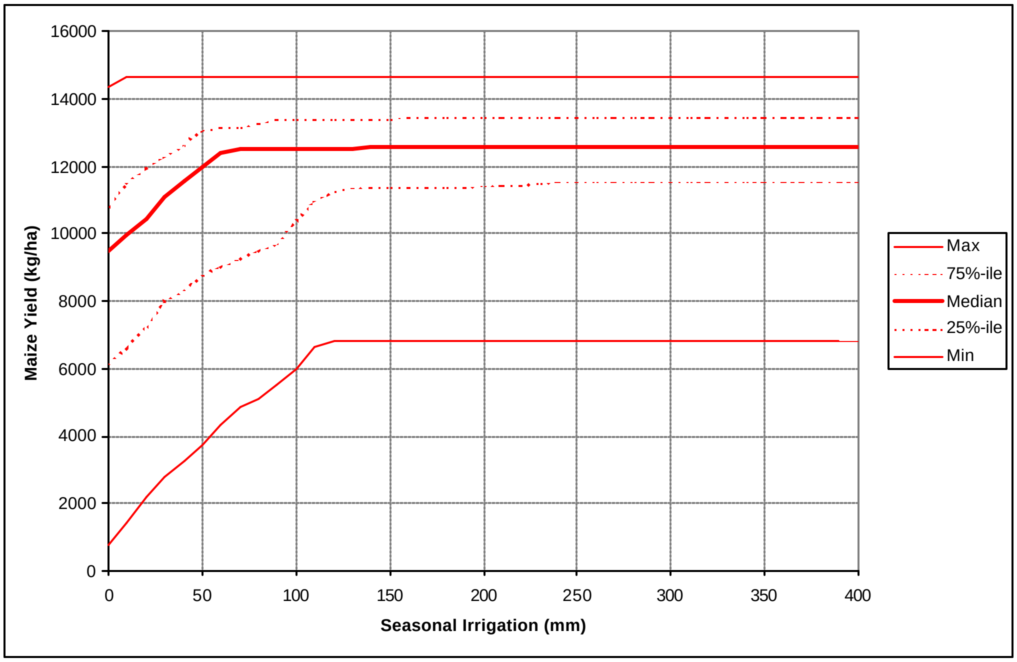

Figure 12a. CWPF-PD for maize grown at East Mitchell County, full study period of 1965-1995.

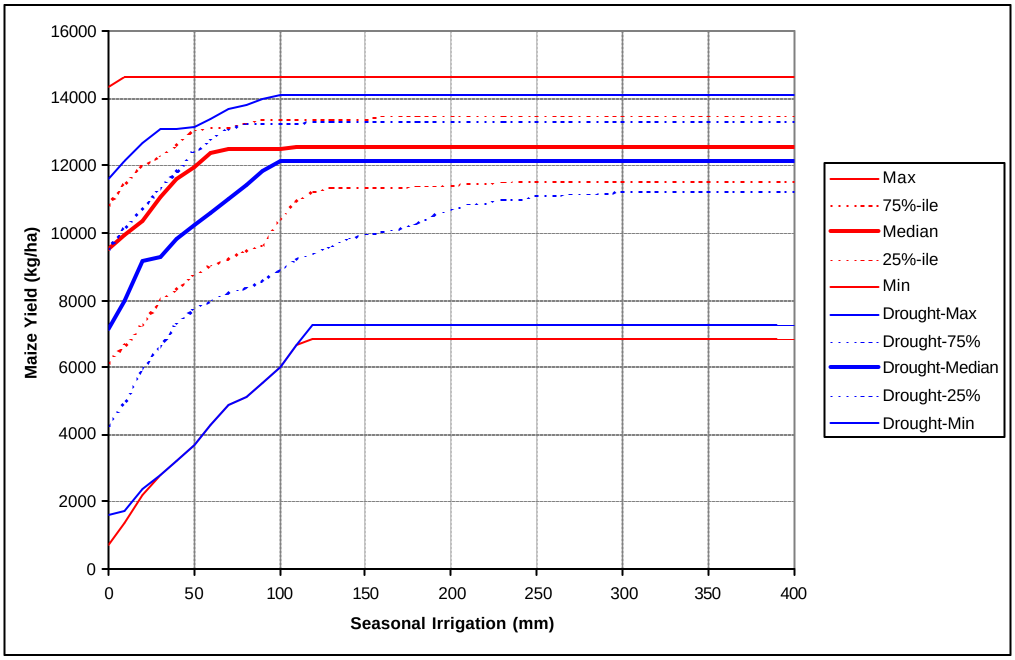

Figure 12b. CWPF-PD's for maize grown at East Mitchell County for full study period (red) and drought seasons alone (blue).

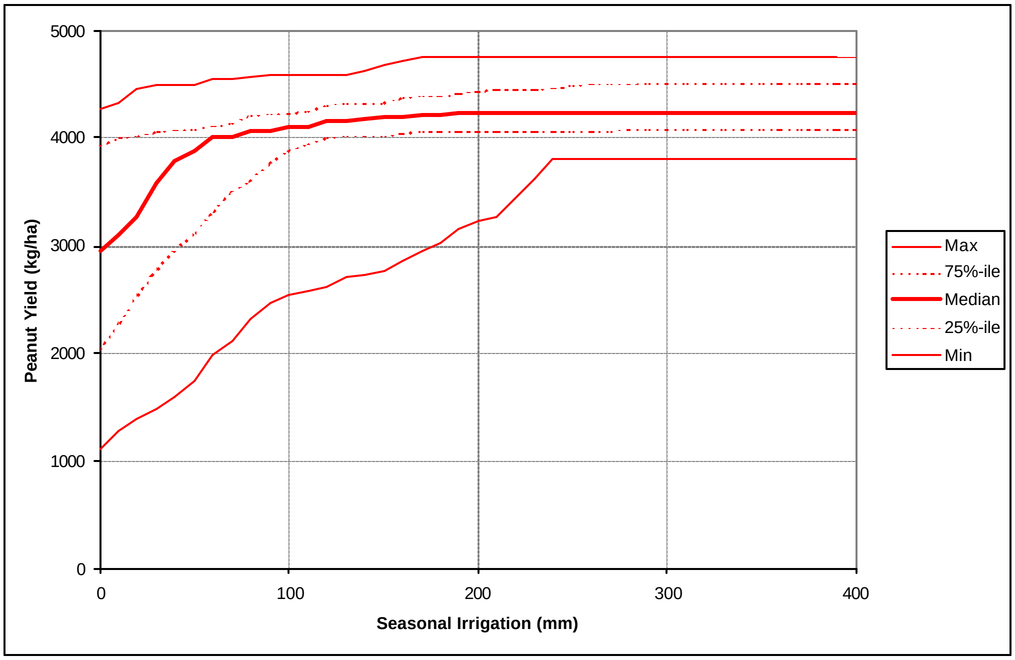

Figure 13a. CWPF-PD for peanuts grown at Southwest Mitchell County, full study period of 1965-1995.

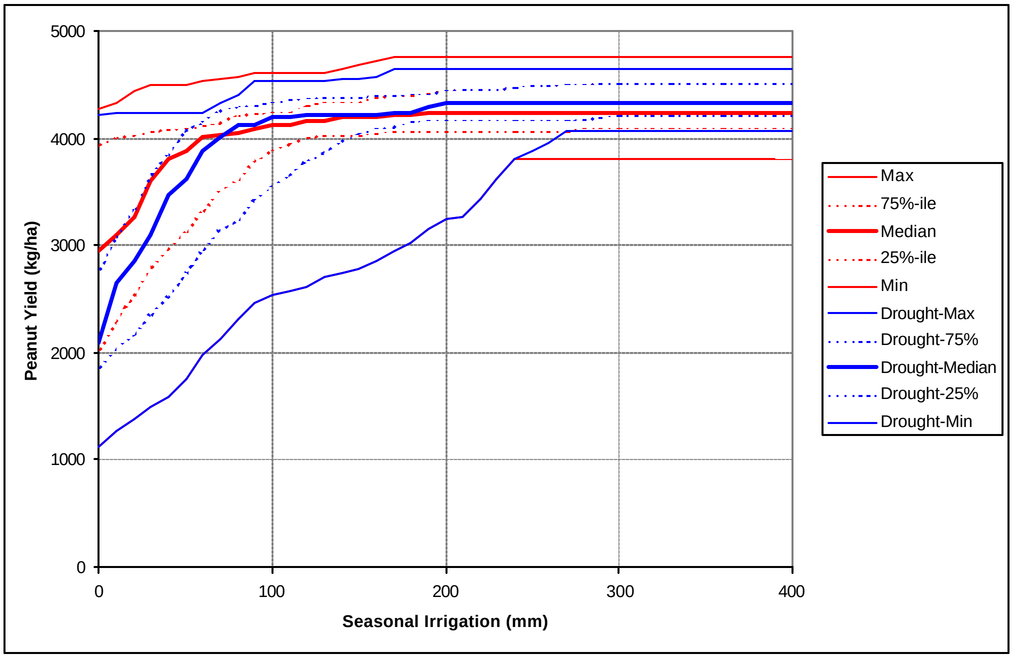

Figure 13b. CWPF-PD's for peanuts grown at Southwest Mitchell County for full study period (red) and drought seasons alone (blue).

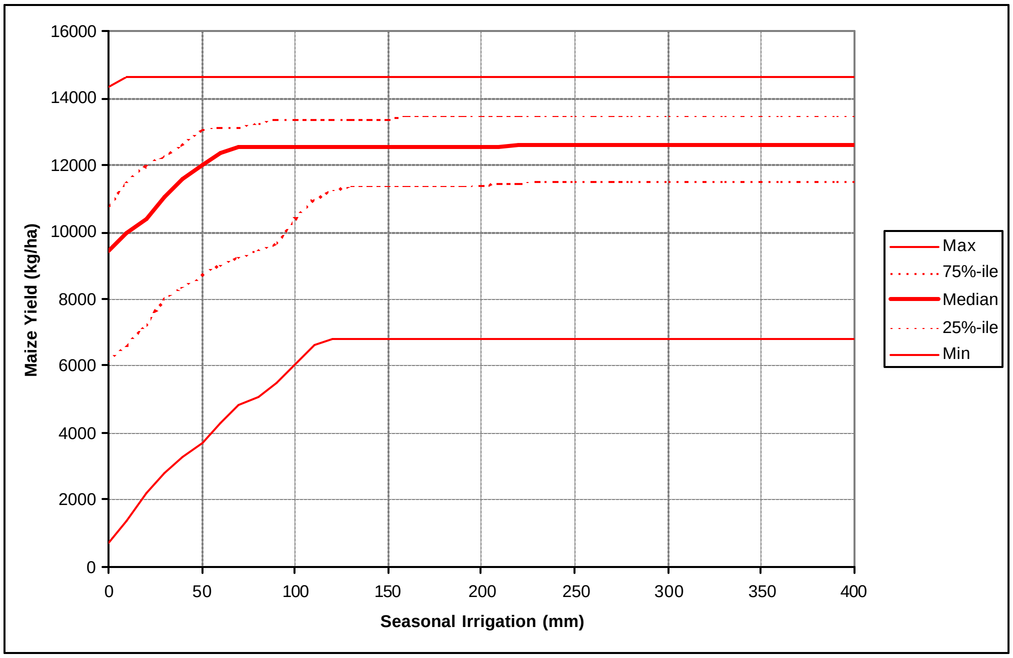

Figure 14a. CWPF-PD for maize grown at Southwest Mitchell County, full study period of 1965-1995.

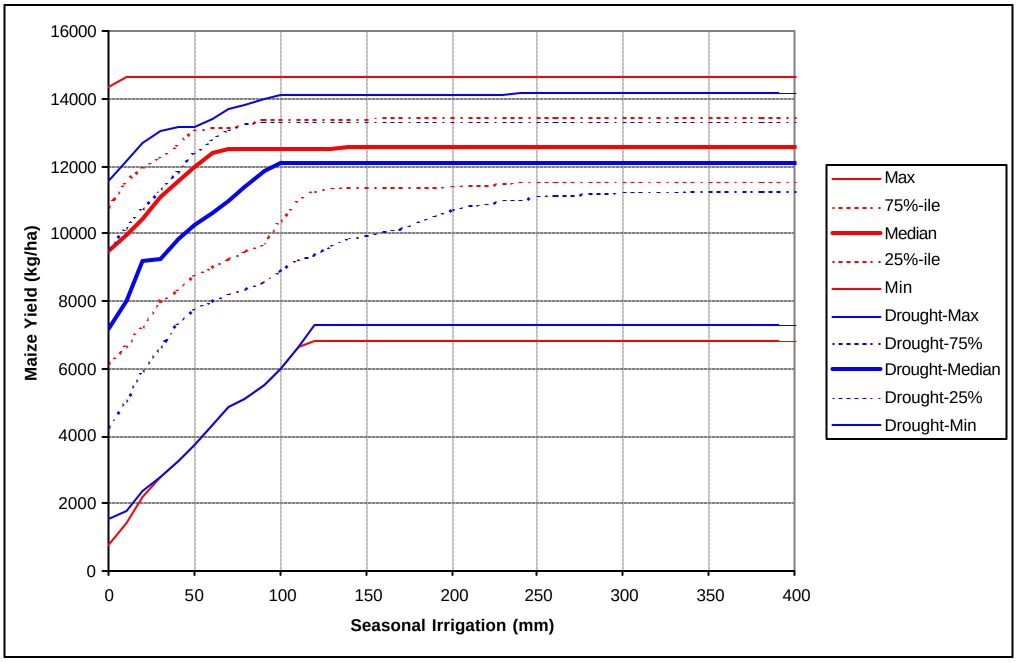

Figure 14b. CWPF-PD's for maize grown at Southwest Mitchell County for full study period (red) and drought seasons alone (blue).

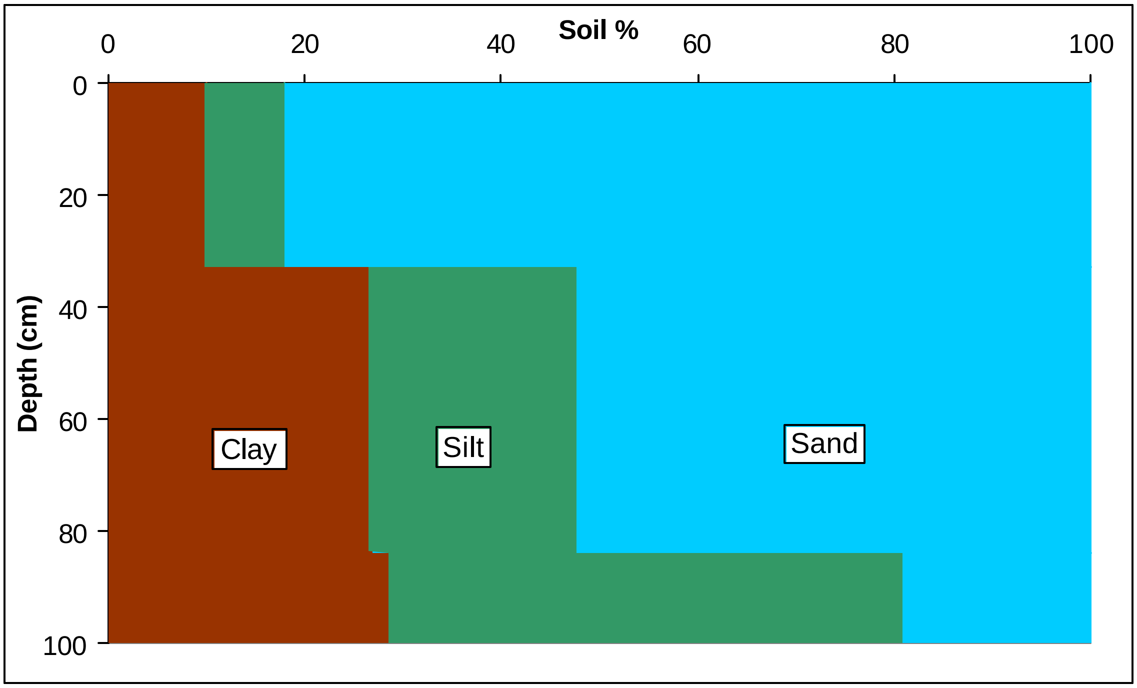

Figure 15a. Profile of soil textural composition for GA050, East Mitchell County.

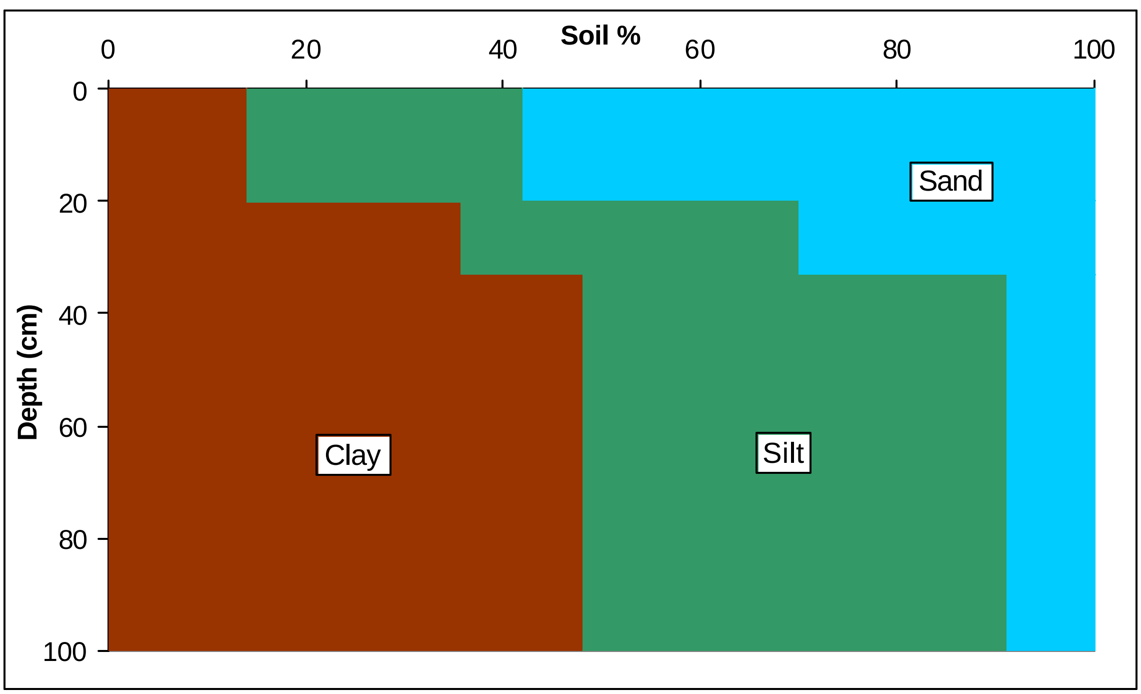

Figure 15b. Profile of soil textural composition for GA060, Southwest Mitchell County.

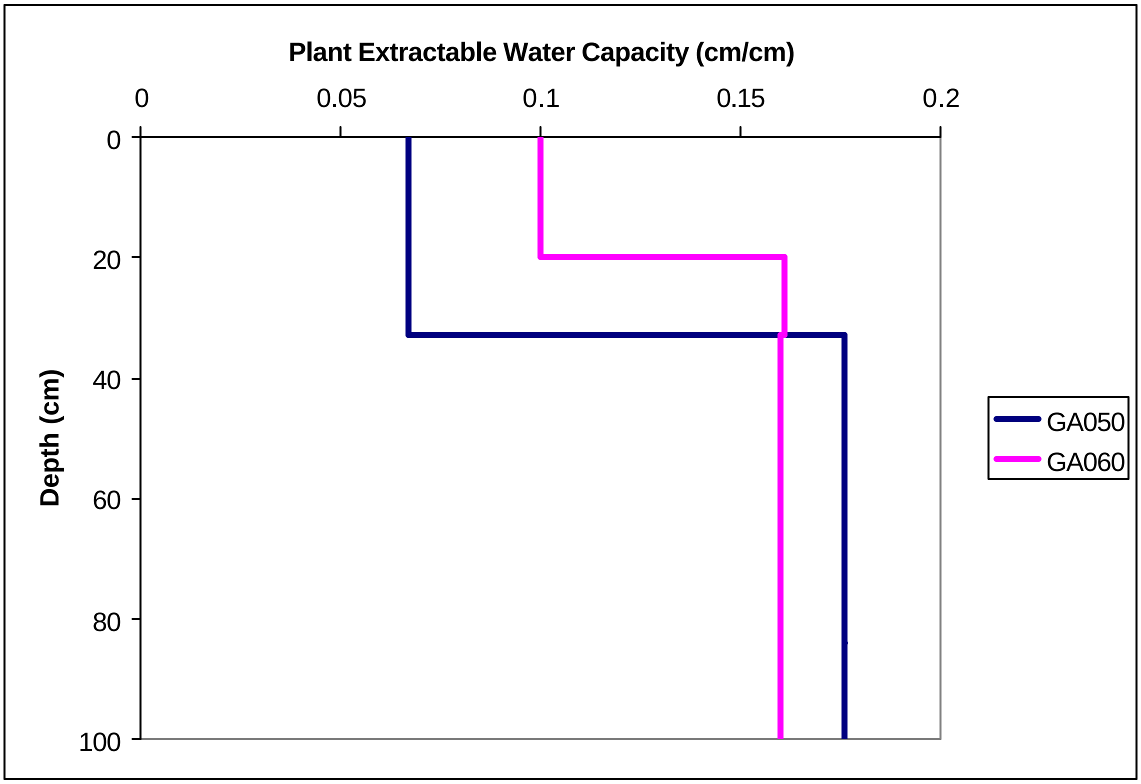

Figure 16. Comparison of profiles of plant extractable water capacity (PEWC) for soils GA050 and GA060. Integration of PEWC over the 100 cm profile yields total PEWC of 14.0 cm for GA050 and 14.8 cm for GA060.